Magnetic Field Effects on Deformation and Fracture Behavior of Ferromagnetic Plates under Bending(強磁性平板の曲げ変形・破壊挙動に及ぼす磁場の影響)

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論　文　内　容　要　旨

Chapter 1　Introduction

There are many devices that operate in magnetic fields. Such devices include magnetic fusion reactors, MHD devices, magnetically levitated vehicles, etc. With the development of high-field superconducting magnets, problems involving the fracture and deformation of solids and structures in high magnetic fields have been become important. The stress and strain state in a magnetizable elastic body is caused not only by mechanical loads but also by magnetic fields. If ferromagnetic materials are used in the high magnetic field, we must consider the effect of induced magnetization.

To design the magnetic fusion reactors it is necessary to consider the possible influence of the magnetic field on the fracture and deformation properties of candidate materials. Ferritic/martensitic stainless steels have been developed for first wall and structural materials applications for commercial fusion reactors. The 12Cr-1Mo-0.5W-0.2C alloy HT-9 is a magnetic stainless steel. It has been extensively tested and shown to resist radiation damage, providing a creep and swelling resistant alternative to austenitic steels. Incoloy alloy 908, a ferromagnetic austenitic alloy, is also a candidate conduit material for large-scale Nb_3Sn superconducting magnets of the International Thermonuclear Experimental Reactor (ITER). Recently, the effect of the magnetic field on the cryogenic fracture toughness of alloy 908 has been investigated using notch tensile and small punch tests. While experiment predicts that magnetic fields will not have a significant effect on the toughness of low-permeability alloy, we should still address the question of whether magnetic fields are expected to influence the fracture and deformation properties of any structural alloy under any conditions.

In this paper, the magnetic fracture and deformation of ferromagnetic plates is investigated to show the effect of induced magnetization. We solve a series of magnetoelastic problems for cracked ferromagnetic plates under bending. Furthermore, we conduct experiments to verify the theoretical model.

Chapter 2 Basic Equations of Magnetoelasticity

In this chapter, we present the basic equations of the linear theory of magnetoelasticity for both soft ferromagnetic and magnetically saturated materials.

Chapter 3 Magnetoelastic Analysis of a Soft Ferromagnetic Plate with a Through Crack under Bending

Following a classical plate bending theory of magnetoelasticity, we consider the bending problem of a soft ferromagnetic plate with a through crack under a uniform magnetic field. The solution of the through crack problem may be useful in studying the surface crack problem by the application of the plate theory-line spring method. The results for the case with a partial crack can be estimated by the formulation of the soft ferromagnetic plate containing a through crack under arbitrary membrane and bending loads, and the solution of the corresponding plane-strain problem for the soft ferromagnetic medium with an edge crack. The cracked plate with simply supported ends is loaded by bending moments, and the magnetic field is perpendicular to the plate surface. By the use of Fourier transforms we reduce the problem to solving a pair of dual integral equations. The solution of the dual integral equations is then expressed in terms of a Fredholm integral of the second kind. The bending moment intensity factor is computed and the influence of the magnetic field on the normalized values is displayed graphically. Allowing the magnetic field to tend to zero, we have the purely elastic problem. The result is evaluated for the martensitic stainless steel HT-9. The magnetic field effect can increase the values of the moment intensity factor. The effect of the magnetic field on the moment intensity factor is more pronounced with increasing the crack-length to plate-thickness and the plate-length to plate-thickness ratios, and the magnetic susceptibility.

Chapter 4 Dynamic Bending of a Soft Ferromagnetic Plate with a Through Crack under a Uniform Magnetic Field

In many cases of strength assessment of structural components from the view point of fracture mechanics, it is necessary to take into account the inertial effects arising due to the dynamic nature of loadings. This chapter deals with the scattering of time harmonic flexural waves by a through crack in a soft ferromagnetic plate under a uniform magnetic field. The plate is engulfed by a uniform magnetic field directed normal to the plate surface and subjected to incident waves that generate vibratory motion in the transverse direction of the plate. Classical plate bending theory for soft ferromagnetic materials including dynamic magnetoelastic effects is applied. A limitation of the theory is that both the crack and incident wave length must be large in comparison with the plate thickness. Fourier transforms are used to reduce the magnetoelastic problem to a pair of dual integral equations which can be further deduced to a Fredholm integral equation of the second kind that is amenable to numerical calculations. The dynamic bending moment intensity factors are determined for different wave frequencies and amplitudes of the magnetic field. Mindlin's plate theory of magnetoelasticity can be made, of course, but our purpose here is to demonstrate the nature of the magnetoelastic coupling using the simplest theory. The elastodynamic plate solution is recovered when the magnetic field tends to zero. The considered soft ferromagnetic material is the martensitic stainless steel HT-9. The existence of the magnetic field produces lager values of the dynamic moment intensity factor. Significant increase in the local moment intensity factor occurs at low wave frequency, and the magnetic field effect dies out gradually as the frequency is increased.

Chapter 5 Singular Moments in a Magnetically Saturated Plate with a Through Crack Subjected to a Uniform Magnetic Field

A ferromagnetic medium is soft magnetic only within a limited range of the magnetization curve and there is a gap between the soft ferromagnetic range and the saturation point. In this chapter, the singular moments in a magnetically saturated martensitic stainless steel plate with a through crack under a uniform magnetic field normal to the plate surface are discussed. The plate is deformed by bending moments at the simply supported ends. Classical plate bending theory for magnetoelastic interactions in magnetically saturated bodies is applied. A solution of the magnetoelastic problem is obtained by the method of dual integral equations and the result is expressed in terms of a Fredholm integral equation of the second kind that is amenable to numerical calculations. The moment intensity factor for the HT-9 plate is computed to exhibit the influence of the magnetic field. The results for the saturation model are compared with those for the soft ferromagnetic model. The effect of the magnetic field on the moment intensity factor for the saturation model is more pronounced than that for the soft ferromagnetic model.

Chapter 6 Dynamic Bending of a Magnetically Saturated Plate with a Through Crack in a Uniform Magnetic Field

This chapter presents the scattering of time harmonic flexural waves by a through crack in a magnetically saturated plate under a uniform magnetic field normal to the plate surface. An incident wave giving rise to moments symmetric about the crack plane is applied. Classical plate bending theory for magnetically saturated materials is extended to include dynamic magnetoelastic effects. Fourier transforms are used to reduce the mixed boundary value problem to one involving the numerical solution of a Fredholm integral equation. Numerical results are obtained for the dynamic bending moment intensity factors with different wave frequencies and amplitudes of the magnetic field. The magnetically saturated plate is assumed to be the martensitic stainless steel HT-9 or the ferromagnetic material Hipernik. The effect of the magnetic field on the dynamic moment intensity factor increases with the increase of the coefficient $\beta^2 = B_0 / \mu_0 H_0$, where B_0 and H_0 are the saturation values of the magnetic induction and the magnetic intensity, and $\mu_0 = 4\pi \times 10^{-7}$ N/A^2 (H/m; H: henry) is the magnetic permeability of the vacuum.

Chapter 7 Experimental and Theoretical Results for Bending of a Soft Ferromagnetic Plate in a Transverse Magnetic Field

The results of an experimental and theoretical investigation of the bending behavior of a soft ferromagnetic cantilever beam-plate in a transverse magnetic field are presented. The theoretical model based on a beam-plate theory for magnetoelastic interactions in a soft ferromagnetic material predicts the deflection and strain for several values of magnetic field and geometrical parameter. The experiments are conducted on ferritic stainless steel SUS430 in the bore of a superconducting magnet at room temperature. Thin rectangular strips are prepared. The specimen is clamped at one end in a brass vise and bent by a concentrated load applied at the other. A laser displacement meter is used to measure the deflection of the loaded end of the specimen. To measure the strain, five strain gages are placed on the specimen. The Young's modulus is determined from the data on deflection for the cantilever specimen. The specific magnetic permeability is also measured with a Vibrating Sample Magnetometer. A superconducting magnet SM-3 with a 220 mm diameter bore at High Field Laboratory for

Superconducting Materials, Institute for Materials Research, Tohoku University, is used to create a magnetic field normal to the wide face of the specimen. The deflection and the strain are recorded as a function of magnetic field. The experiments show the predicted increase in the deflection and strain with increasing the magnetic field. The magnetic field effect tends to increase with increasing the length to thickness ratio. No dependence of bending behavior with the magnetic field on the width is observed. The theoretical results agree very well with the experimental data.

Chapter 8 Testing and Magnetoelastic Analysis of a Soft Ferromagnetic Plate with an Internal Crack under Bending

Experimental evidence and a theoretical model are presented for the bending of a through-cracked soft ferromagnetic plate with fixed ends in a magnetic field. The theoretical model based on a classical plate bending theory for magnetoelastic interactions in a soft ferromagnetic material is used to calculate the magnetic moment intensity factor. The experiments are conducted in the bore of a superconducting magnet at room temperature to verify the theoretical analysis results. The method of strain gages is used to determine the magnetic moment intensity factor. Ferritic stainless steel SUS430 is used as specimen material. The fixed-end through-cracked specimen is bent by a normal line load applied at the center of the plate and is permeated by a uniform static magnetic field normal to the plate surface. A five-element strip gage is installed perpendicular to the crack line. The sensors on this type of strip gage have an active length of 1 mm and are on 2 mm centers. The strains are recorded as a function of magnetic field. The magnetic field increases the moment intensity factor. The magnetic moment intensity factor estimated from the measured strains is in good agreement with theoretical calculations.

Chapter 9 Evaluation of Magnetic Moment Intensity Factors for Cracked Soft Ferromagnetic Plates using Strain Gages

This chapter presents the results of a study on the effect of magnetic fields on the moment intensity factors in through-cracked soft ferromagnetic plates with fixed ends. The experiments are conducted on a ferritic stainless steel with through-cracked plate specimen geometries in a uniform, static transverse magnetic field. Strain gages are used to evaluate the magnetic moment intensity factors. The experimental results are given for a single internal crack, a single edge crack, and two symmetric edge cracks. The moment intensity factor is found to increase with increasing the magnetic field. No dependence of moment intensity factor with the magnetic field on the load is observed. The magnetic field effect becomes more pronounced as specimen-length to specimen-thickness and the crack-length to specimen-thickness ratios increase.

Chapter 10 Conclusions

The main results and conclusions of the present research work are summarized. The applied magnetic field tends to intensity the deformation and fracture behavior of ferromagnetic plates. Therefore, use of ferromagnetic materials in superconducting structures and magnetomechanical devices should involve the studying the effect of the magnetic field on strength and fracture properties.

論文審査結果の要旨及び学力確認結果の要旨

論文提出者氏名	堀口　勝三
論　文　題　目	Magnetic Field Effects on Deformation and Fracture Behavior of Ferromagnetic Plates under Bending (強磁性平板の曲げ変形・破壊挙動に及ぼす磁場の影響)
論文審査及び 学力確認担当者	主査　教　授　進藤裕英　　教　授　山中一司 教　授　川崎　亮

論文審査結果の要旨

本論文は、超電導応用機器の設計・開発及び信頼性・安全性評価のための曲げを受ける強磁性平板の強磁場変形・破壊挙動に関する理論的・実験的研究成果をまとめたもので、全編１０章から成る。

第１章の序論では、超電導応用技術における先端デバイス（磁気閉じ込め方式核融合デバイス等）の開発動向及び本研究で対象とした曲げによる強磁性平板の変形･破壊挙動に及ぼす磁場の影響解明に関する研究の位置付けを述べると共に、本研究の目的と意義を明らかにしている。

第２章では、曲げを受ける強磁性平板の強磁場変形・破壊挙動を理論解析するため、解析モデルを設定し、磁気弾性基礎式を誘導している。

第３～６章は、板面に垂直な一様磁場内における強磁性平板の曲げ問題を対象に、基本的な磁気破壊力学的挙動を解明したもので、積分変換を用いた厳密な理論解析を行っている。先ず、第３章では、貫通き裂を有する両端単純支持の軟磁性平板に曲げモーメントが作用する場合を考え、モーメント拡大係数に及ぼす磁気弾性相互干渉の影響を解明している。また、第４章では、軟磁性平板の貫通き裂による磁気たわみ波散乱問題の理論解析に成功し、き裂の動的磁気弾性挙動を明らかにしている。続く第５章及び第６章は、貫通き裂を有する飽和磁性平板の曲げに関する磁気弾性解析に成功したもので、第５章では、両端単純支持平板の曲げ問題を、第６章では、き裂による磁気たわみ波散乱問題を取り上げ、磁気的飽和状態における強磁性平板のき裂先端近傍における特異モーメントに及ぼす磁場の影響を解明している。

第７～９章では、軟磁性平板の磁気弾性変形・破壊挙動解明のための実験解析法を開発しており、先ず、第７章で、板面に垂直な一様磁場内において、先端に集中荷重の作用を受ける軟磁性片持ちはり板のたわみ・ひずみに及ぼす磁場の影響を理論的･実験的に解明し、磁気弾性相互干渉に関する理論の妥当性を検証している。続く第８章では、貫通き裂を有する両端固定軟磁性平板のモーメント拡大係数に及ぼす磁場の影響を理論的・実験的に解明しており、内部き裂を対象に、ひずみゲージ法を用いて磁気モーメント拡大係数を評価し、理論解析結果と比較してき裂の磁気弾性相互干渉に関する理論の妥当性検証に成功している。また、第９章では、内部・縁き裂を有する平板状試験片の磁気弾性曲げ挙動を実験的に解明している。

最後に、第１０章の結論では、各章で述べた内容を概括すると共に、得られた知見を整理して本論文の統括としている。

以上要するに、本研究は、強磁性平板の曲げ変形・破壊挙動に及ぼす磁場の影響に関する理論・実験解析に成功し、超電導応用機器の構造健全性評価に資する結果を提供したもので、材料加工プロセス学の発展に寄与するところが少なくない。

よって、本論文は博士（工学）の学位論文として合格と認める。

学力確認結果の要旨

平成１５年１２月１５日、審査委員ならびに関係教官出席のもとに、学力確認のための試問を行った結果、本人は材料加工プロセス学に関する十分な学力と研究指導能力を有することを確認した。

なお、英学術論文に対する理解力よりみて、外国語に対する学力も十分であることを認めた。

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本論文は、超電導応用機器の設計・開発及び信頼性・安全性評価のための曲げを受ける強磁性平板の強磁場変形・破壊挙動に関する理論的・実験的研究成果をまとめたもので、全編１０章から成る。

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